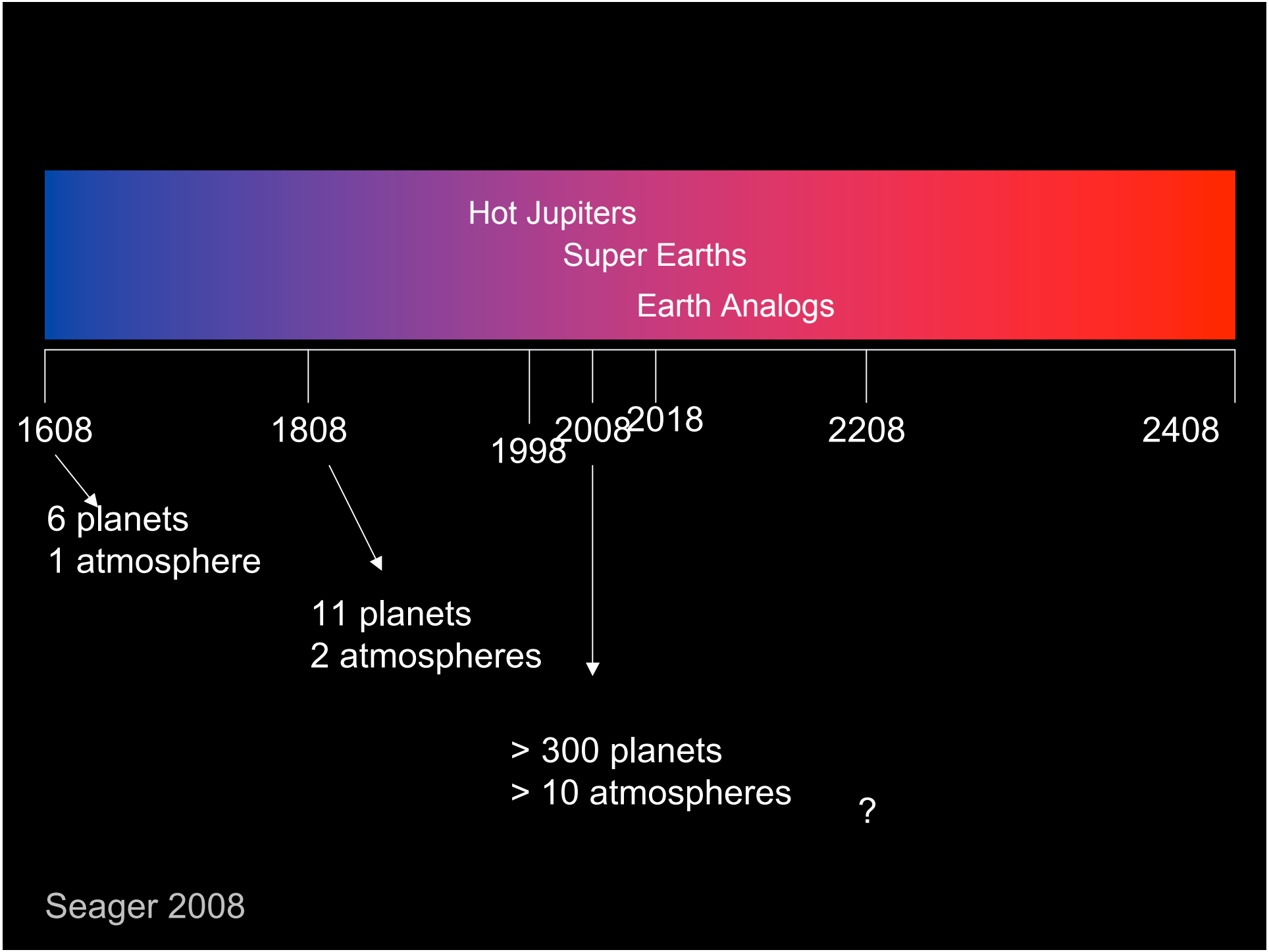
From Hot Jupiters to Hot Super Earths and Beyond

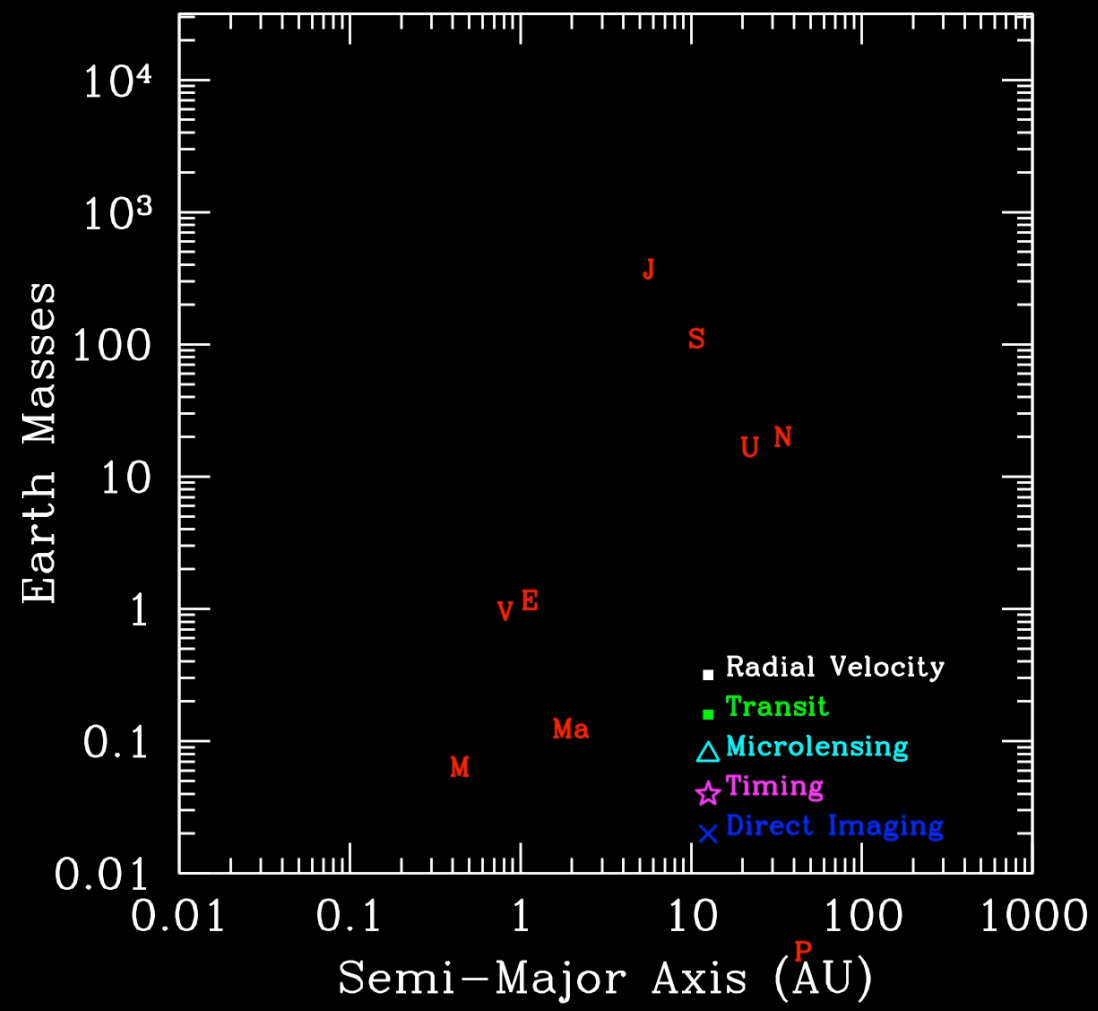
Sara Seager

MIT

Seager 2008


Hot Jupiters
Super Earths
Earth Analogs
1608
1808
1998
2008
2018
2208
2408
6 planets
1 atmosphere
11 planets
2 atmospheres
> 300 planets
> 10 atmospheres
?
Seager 2008

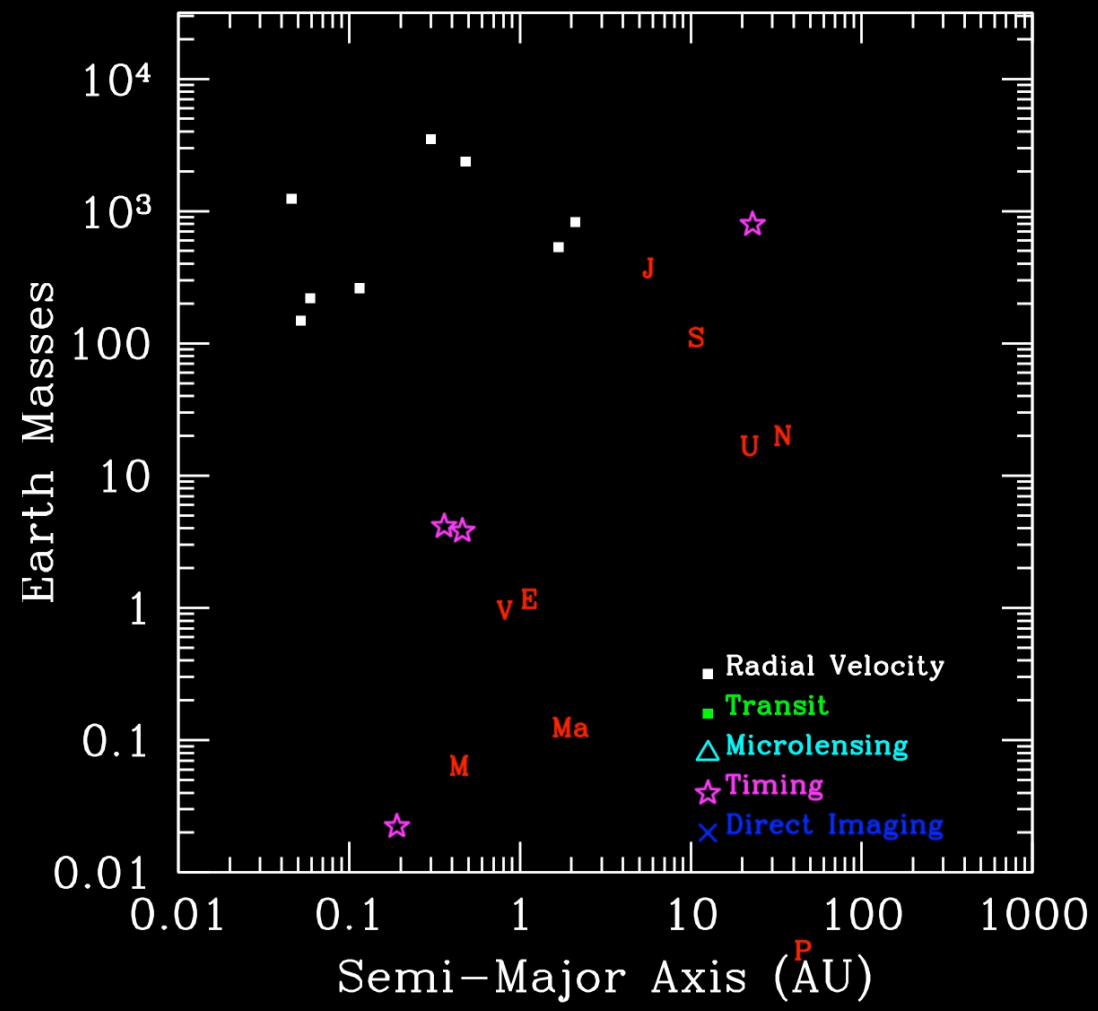
Known Planets 1994



Seager 2008

Based on data compiled by J. Schneider

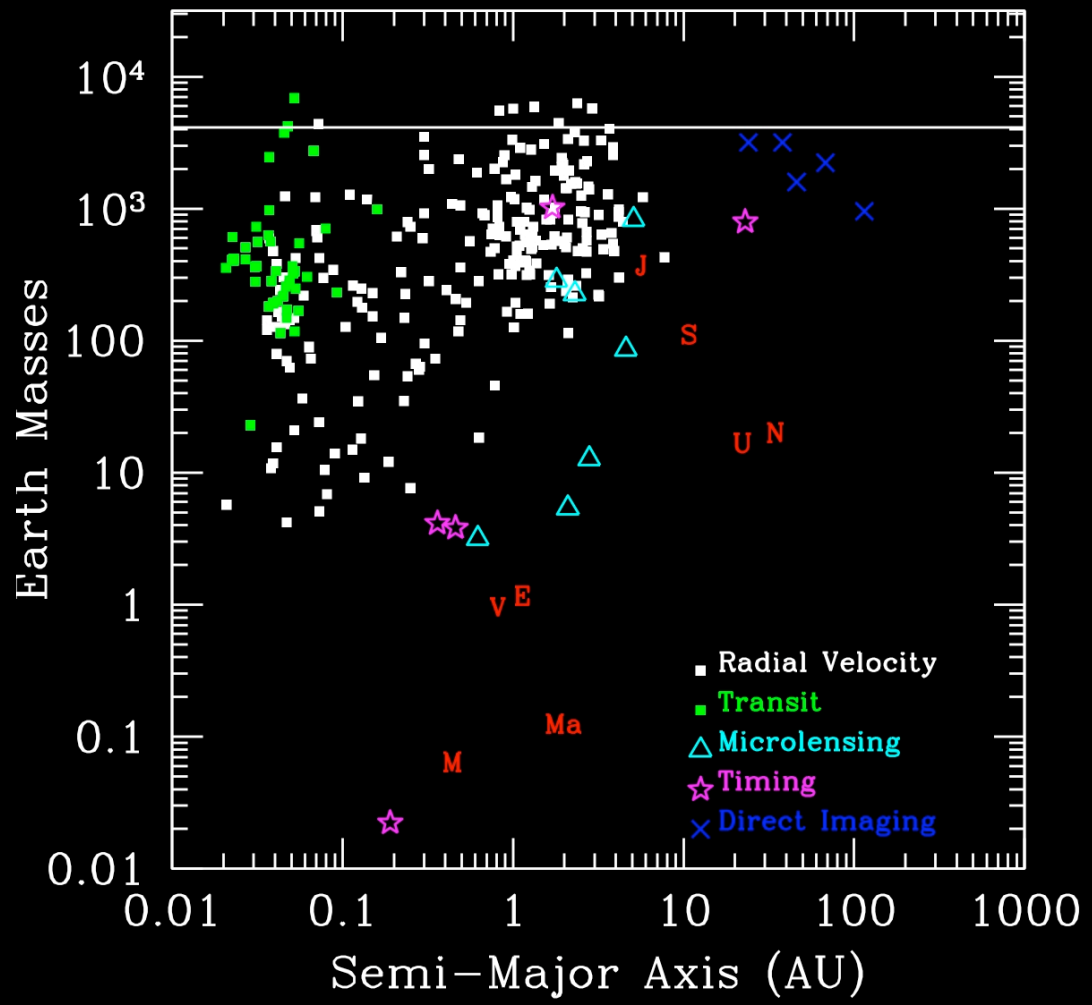
Known Planets 1996



Seager 2008

Based on data compiled by J. Schneider

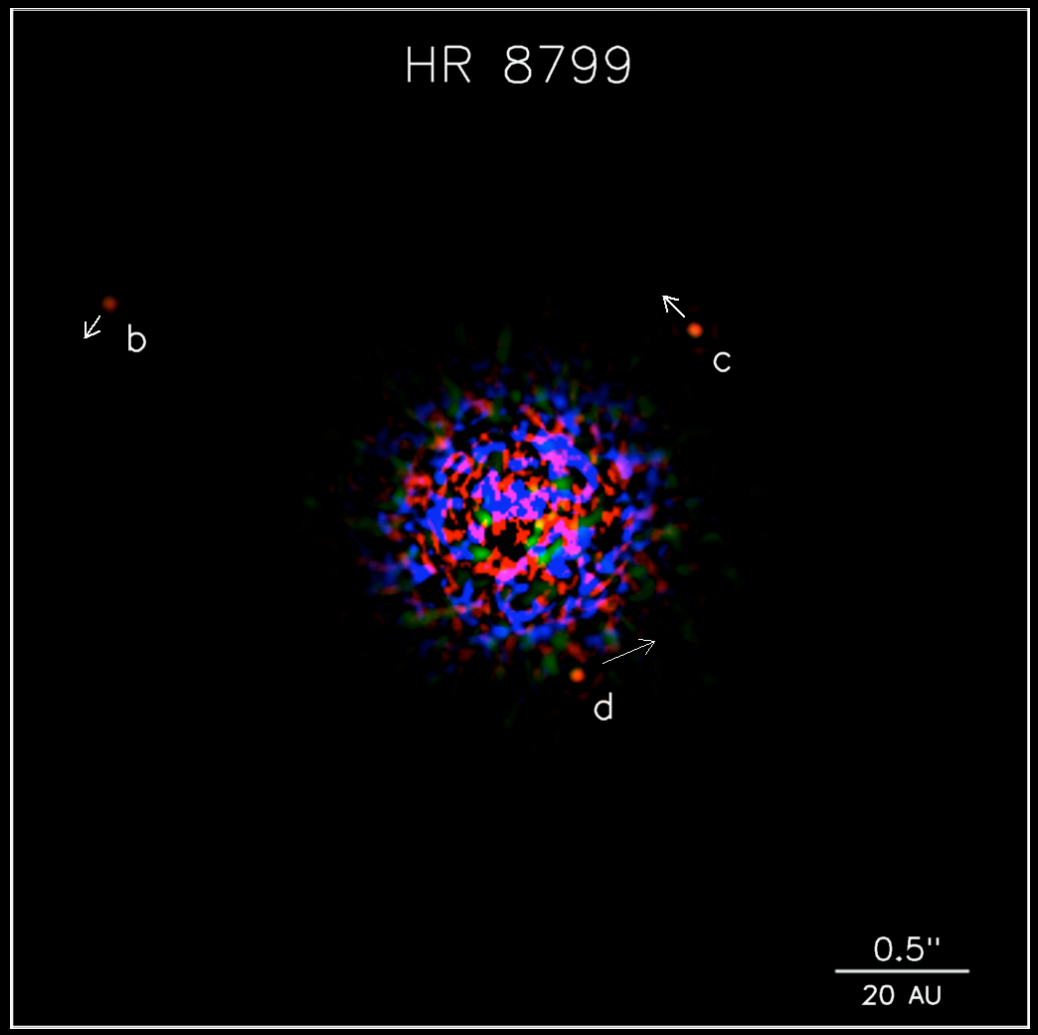
Known Planets 2008



Seager 2008

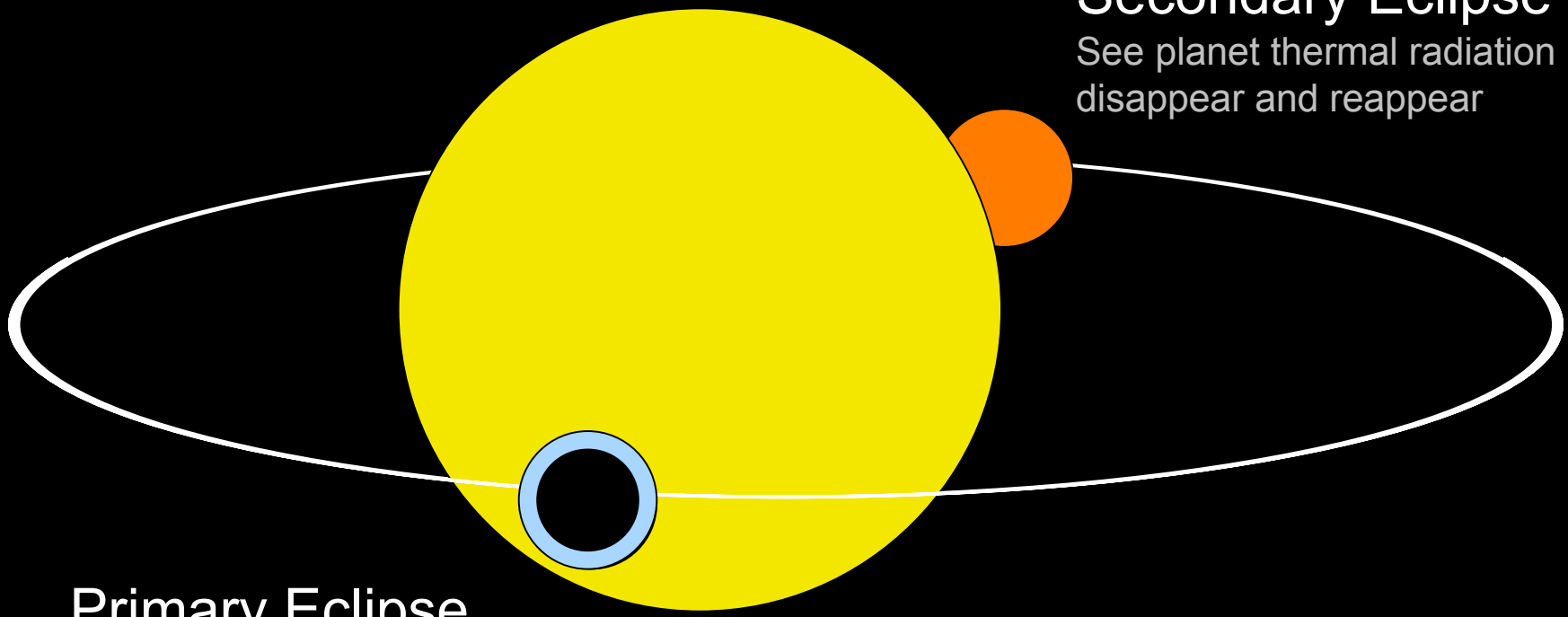
Based on data compiled by J. Schneider

1) Direct Imaging



Marois et al. 2008

2) Transiting Exoplanets



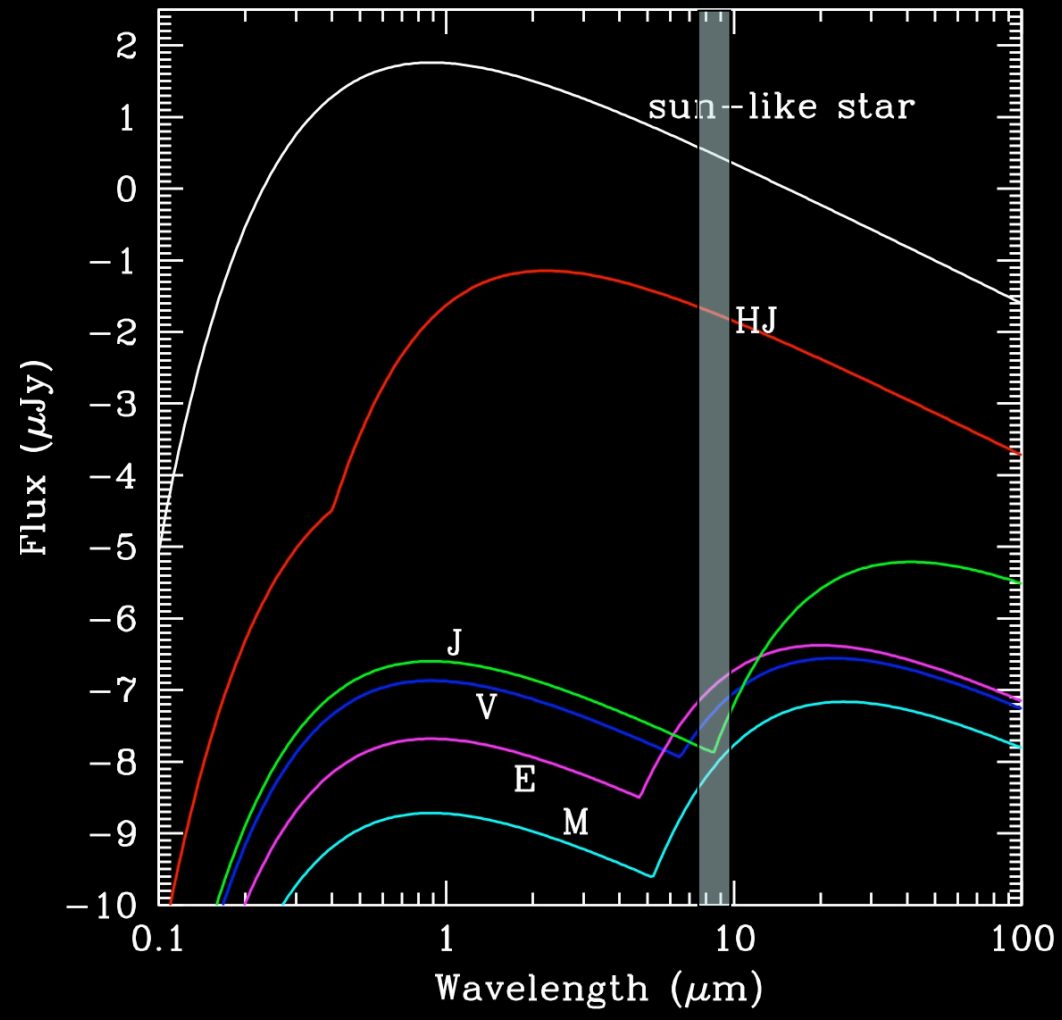
Secondary Eclipse
See planet thermal radiation disappear and reappear

Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere

Learn about atmospheric circulation from thermal phase curves

Seager 2008

Planet-Star Flux Ratio



Solar System at 10 pc

Seager 2003

Hot Jupiters to Hot Super Earths and Beyond

Spitzer's Legacy: Hot Jupiters

Hot Super Earths

Beyond

Seager 2008

Spitzer Exoplanets

Confirmation: Hot Jupiters are Hot

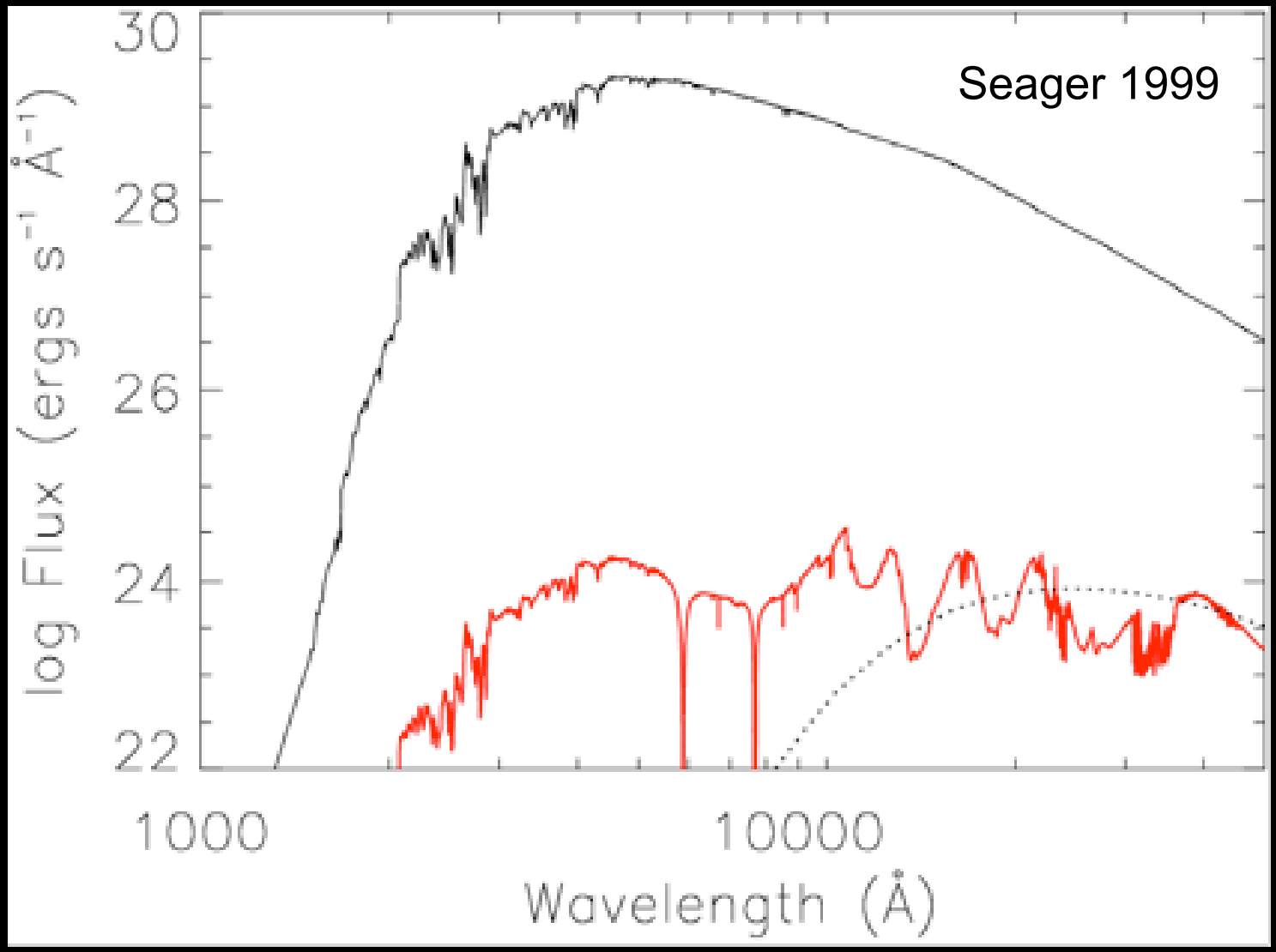
Atmospheric Water Vapor

Thermal Inversion

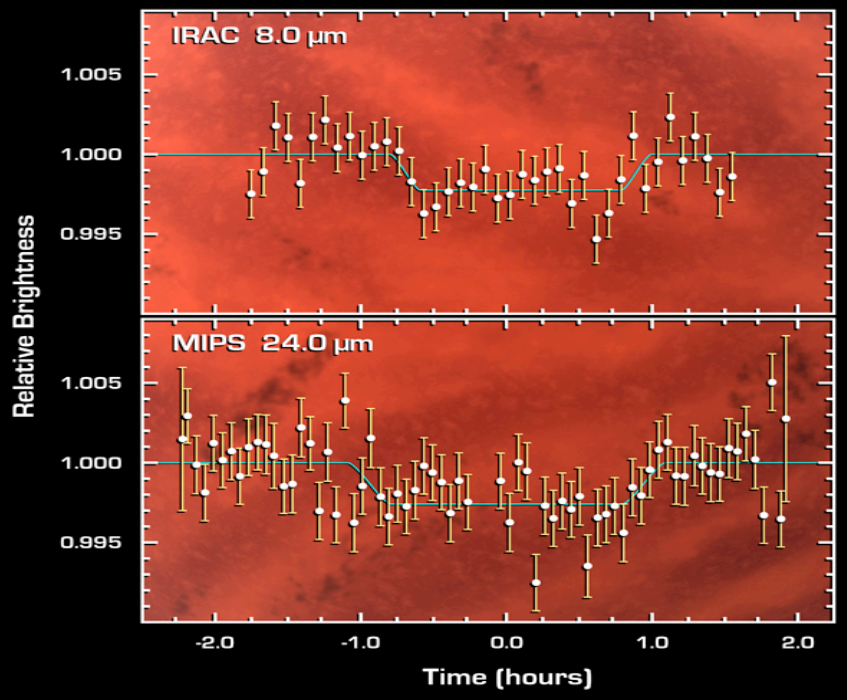
Day-Night Temperature (In)variation

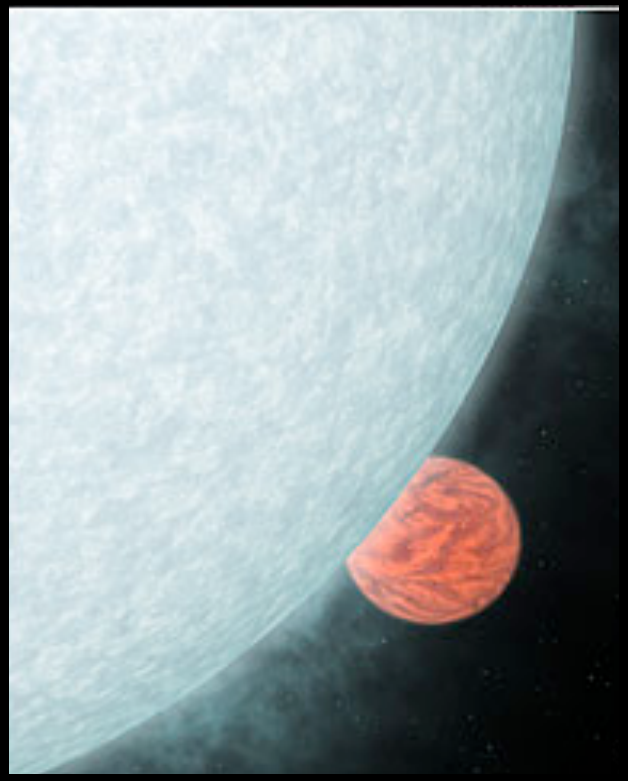
Seager 2008

A Theoretical Hot Jupiter Spectrum



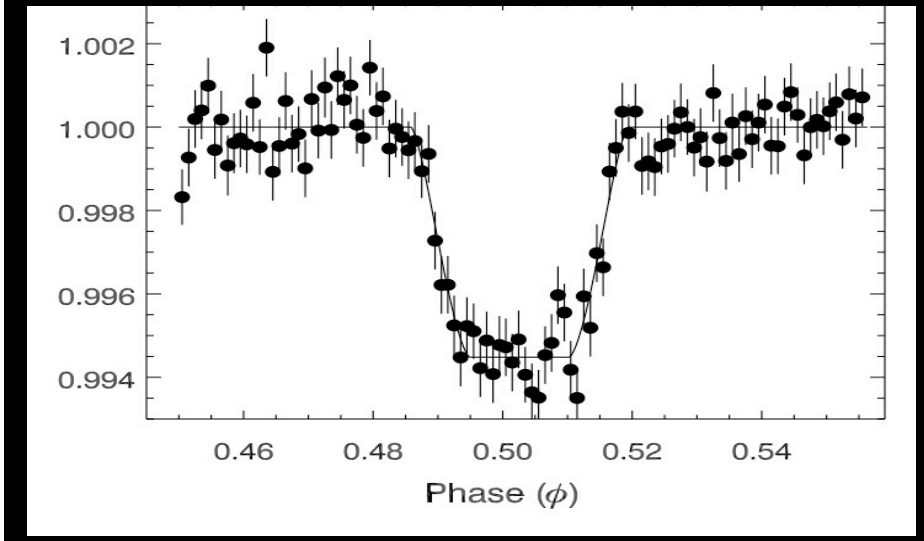
Secondary Eclipse Thermal Emission





Deming, Seager, Harrington, Richardson 2005
Charbonneau et al. 2005

Secondary Eclipse Thermal Emission

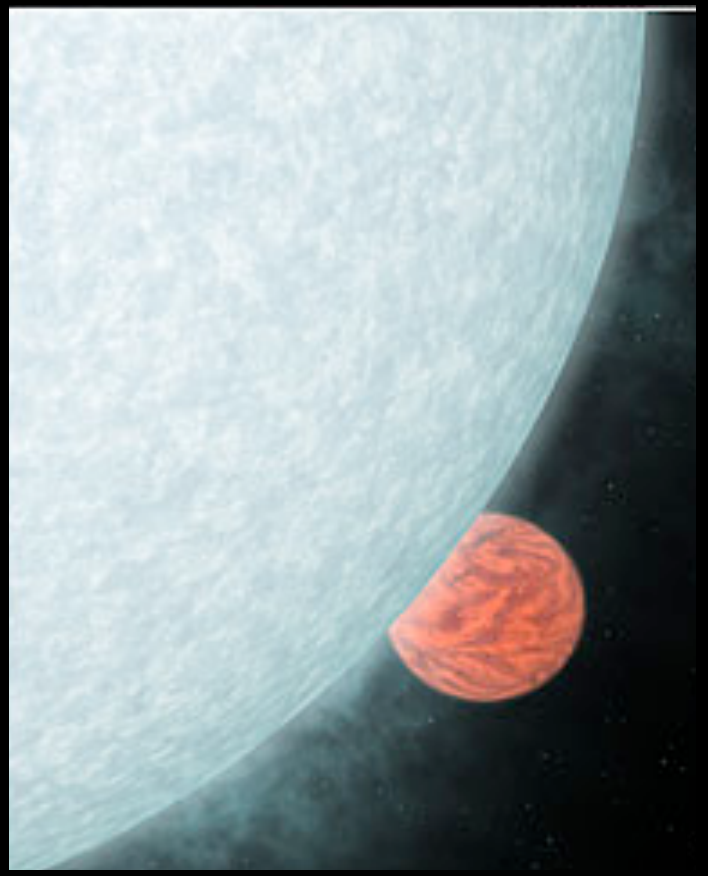


HD189733 16 μm

T_b = 1117+/-42 K

T_{eq} = 1100 K

Contrast: $T_p/T_*(R_p/R_*)^2 \sim 10^{-3}$



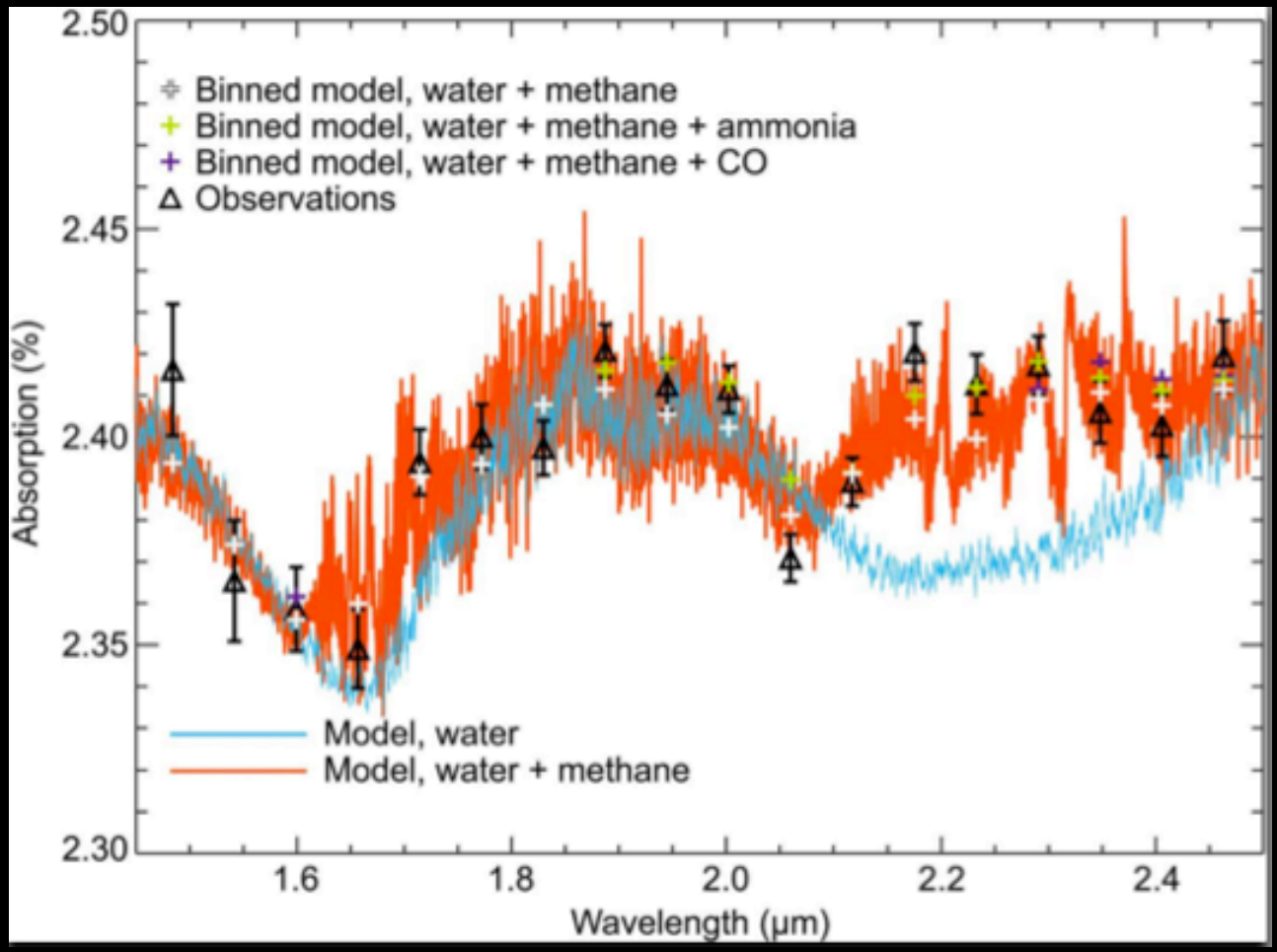
Deming, Harrington, Seager, Richardson 2006

Confirmation of a Model

Hot Jupiters are hot! They are heated externally by their parent stars. Confirmation of a basic theoretical picture.

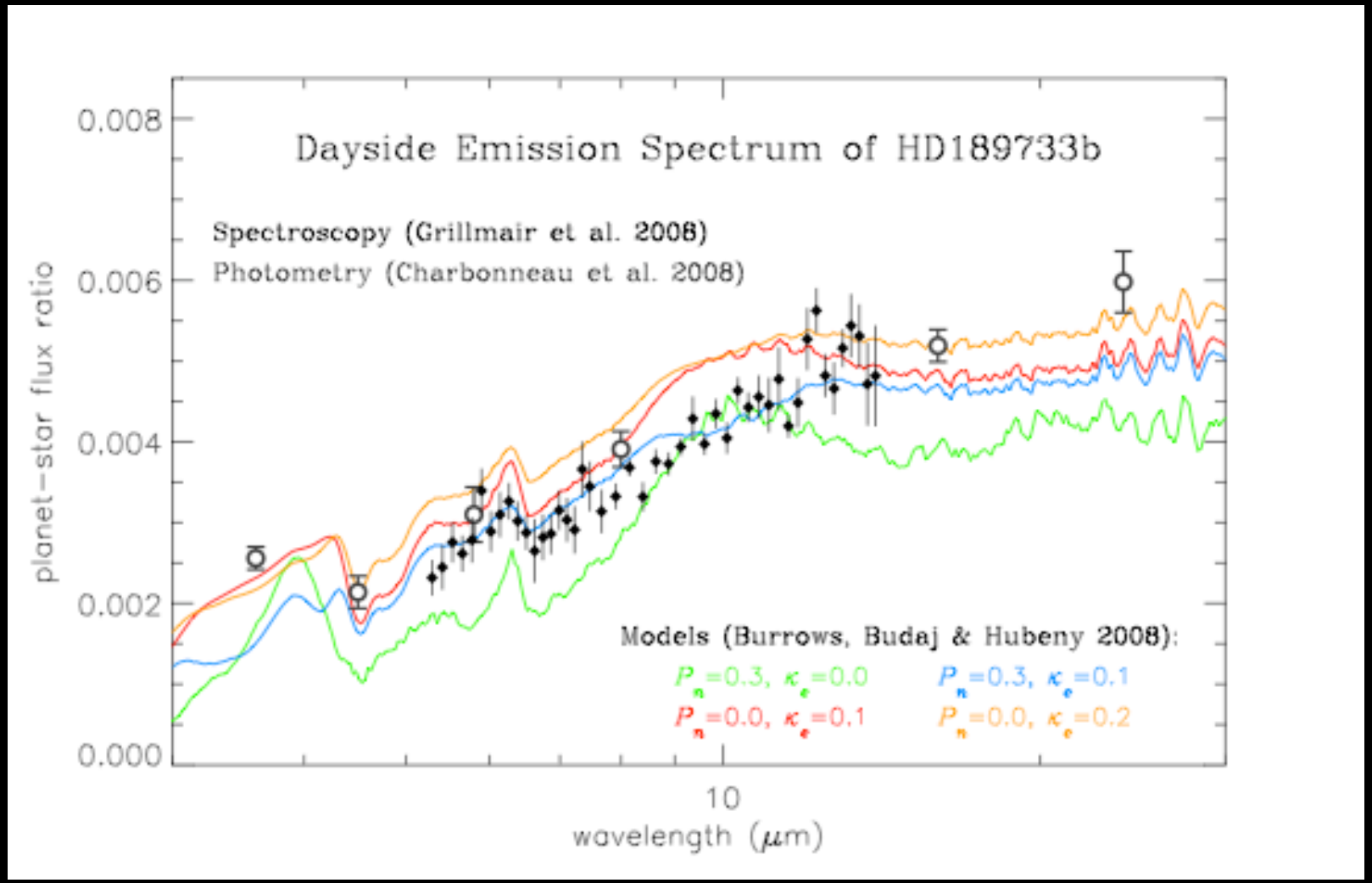
Seager 2008

HD 189733 Transmission Spectrum



Water vapor in transmission using HST.
Swain et al. (2008).

HD 189733 Thermal Emission



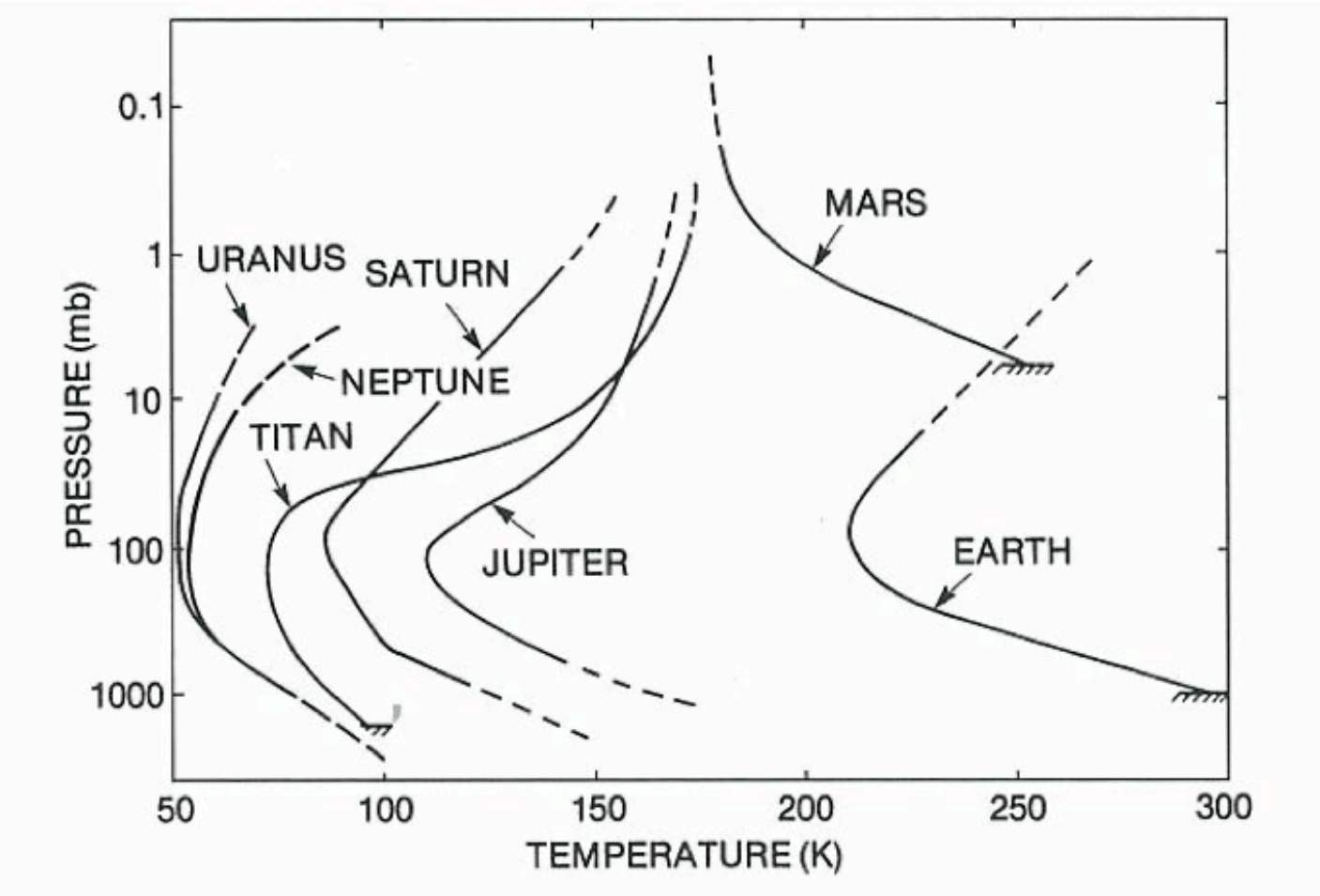
Carl Grillmair et al. 2008 Nature December 11, 2008

Water Detection

Water vapor detection: a second confirmation of the basic picture of hot Jupiters. At T ~ 1000 - 2000K water vapor is unavoidable (unless C/O > 1).

Seager 2008

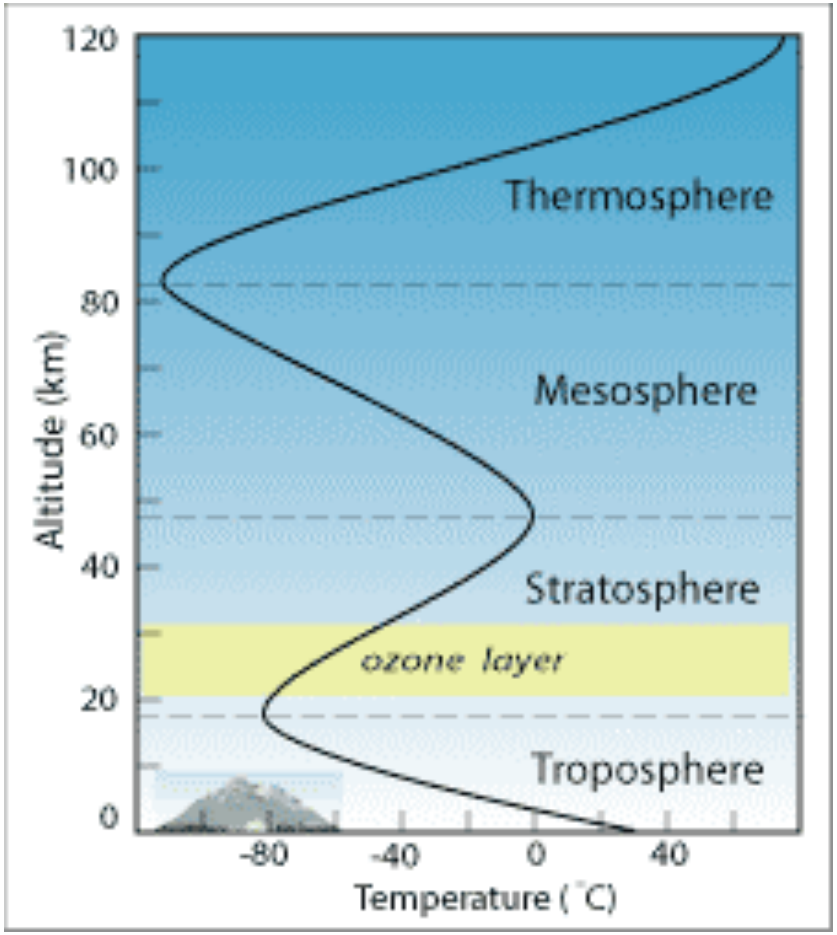
Thermal Inversion



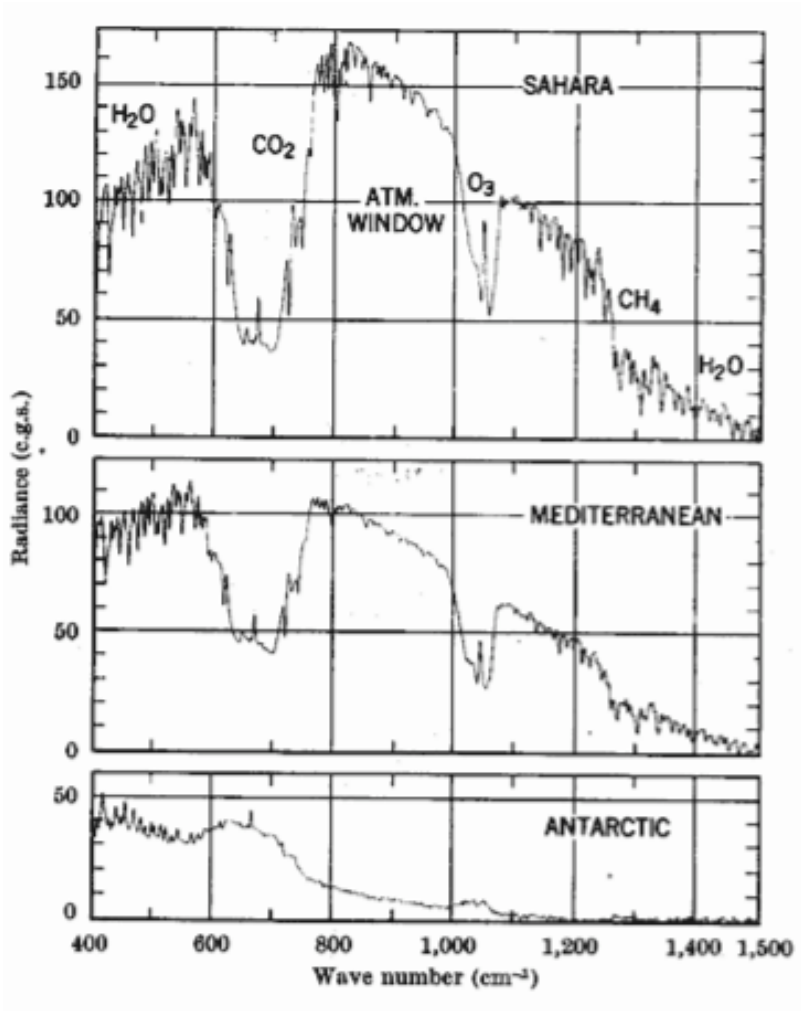
Hanel et al.

Seager 2008

Earth's Thermal Structure

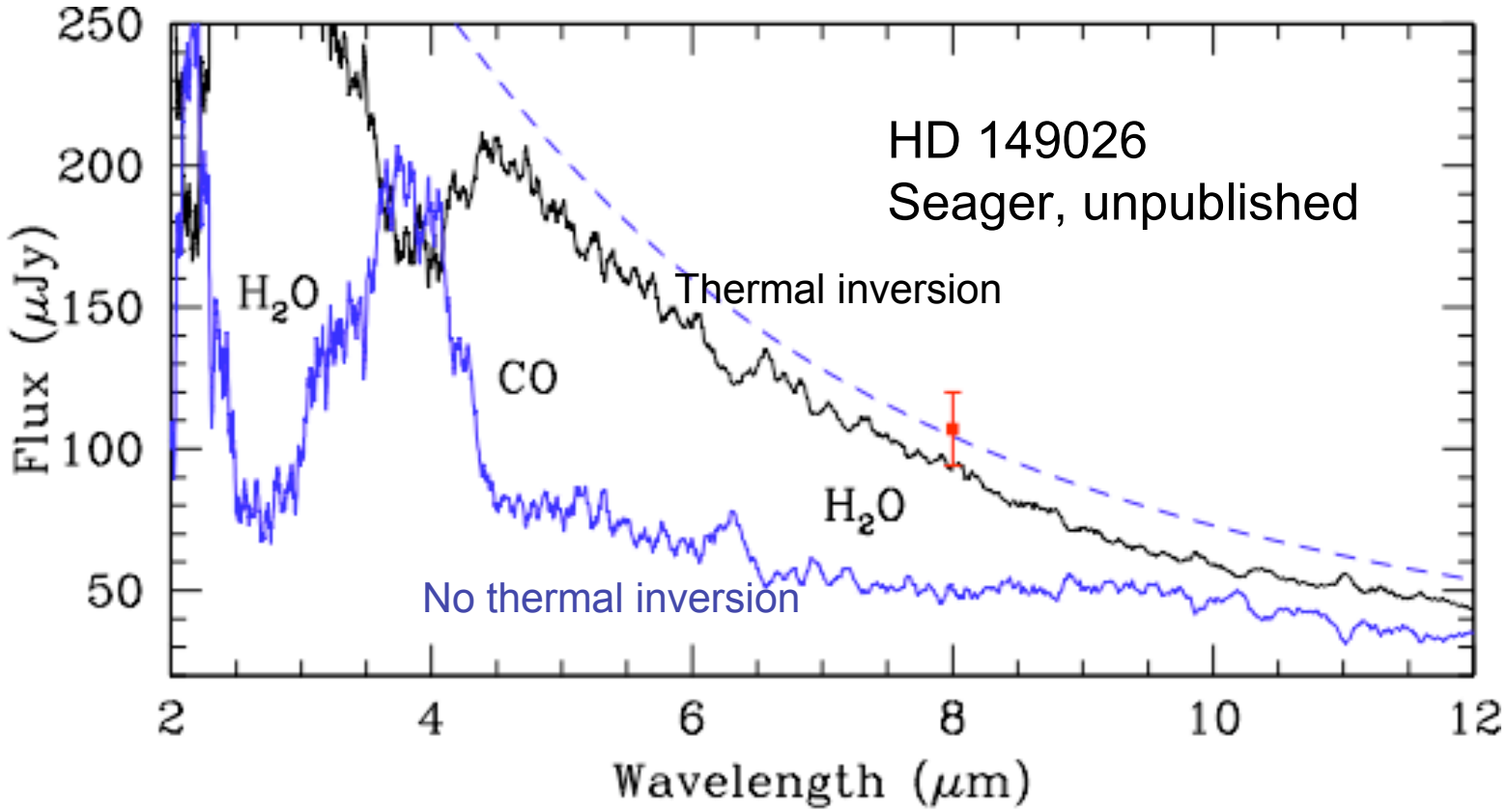


Seager 2008



Hanel 1970

Thermal Inversion



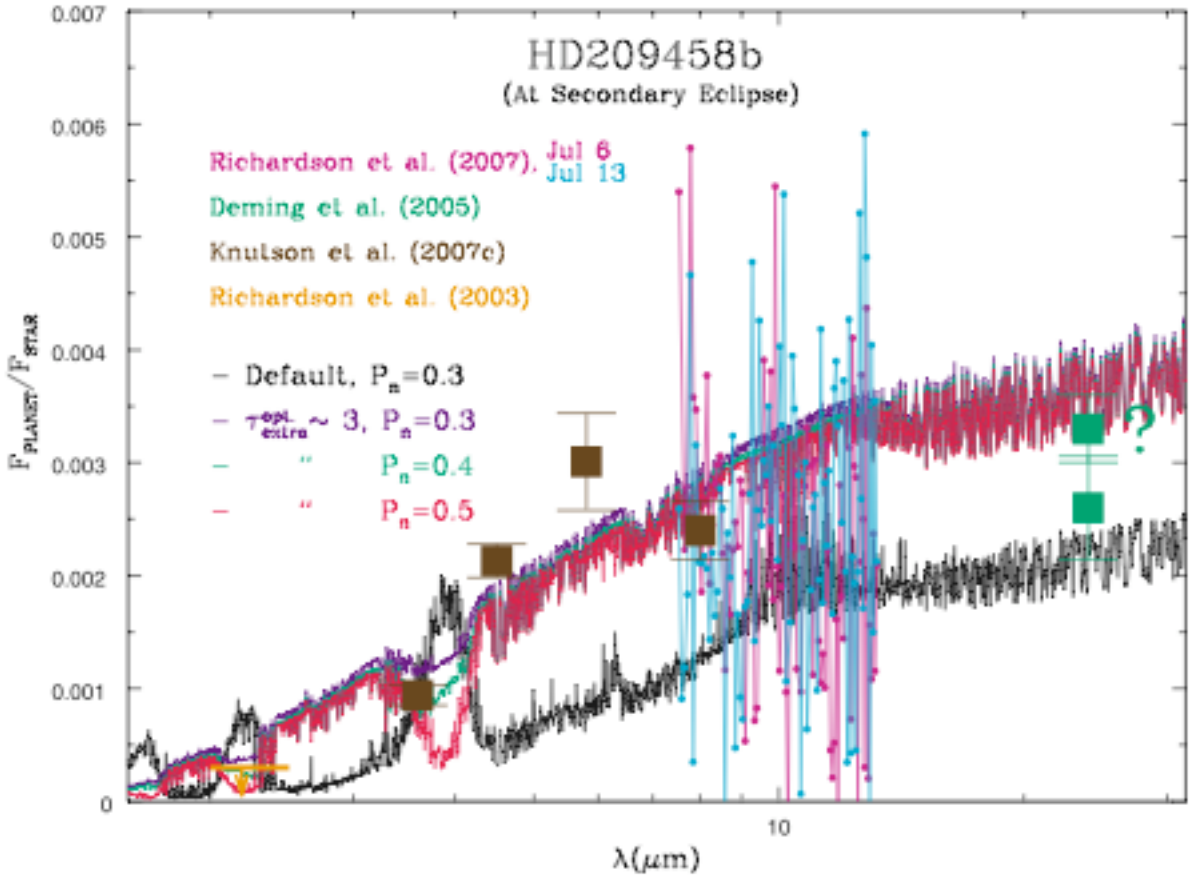
T_b = 2300 +/-200 K

T_{eq} = 1740 K

Data point from Harrington et al. 2007

$$T_{eq} = T_* \left[\frac{R}{a}\right]^{1/2} \left[f(1-A_B)\right]^{1/4}$$

Thermal Inversion



Water vapor/thermal inversion on HD209458b

Knutson et al. 2008, Burrows et al. 2007

Thermal Inversion

Some hot Jupiters have strong thermal inversions (if we assume water vapor). These planets only show emission features. The responsible absorbers are not fully identified.

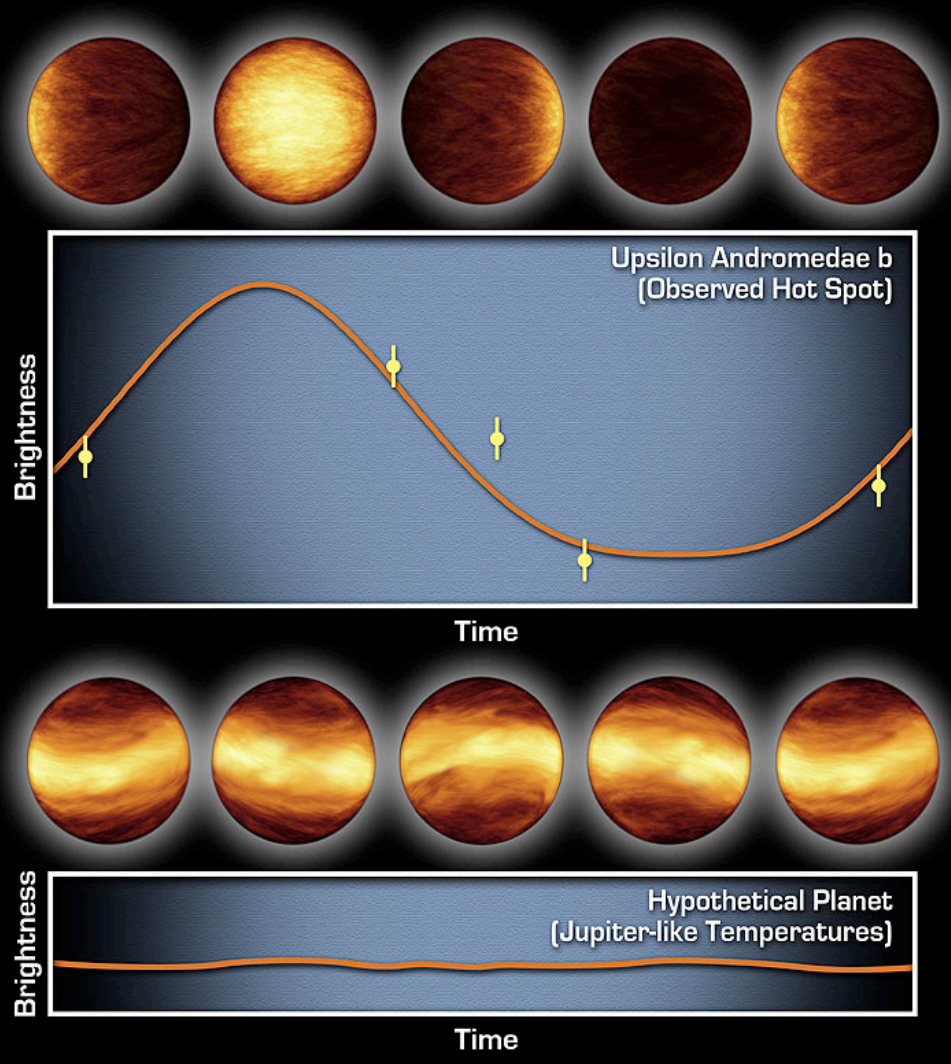
Seager 2008

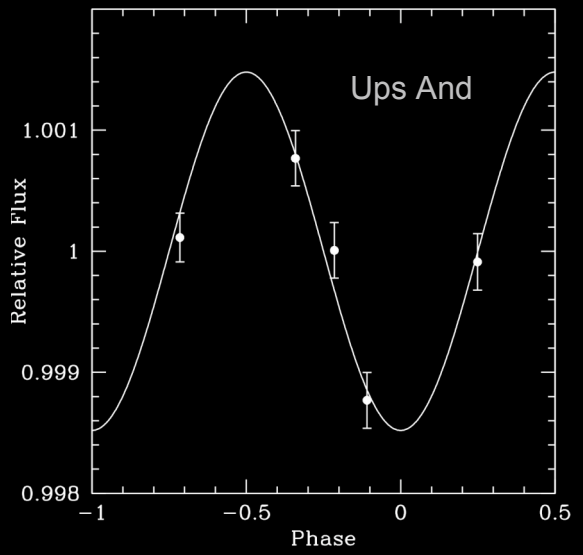
Temperature Gradients

Hot Jupiters are tidally locked with a permanent day side and night side. Are they hot on one side and cold on the other?

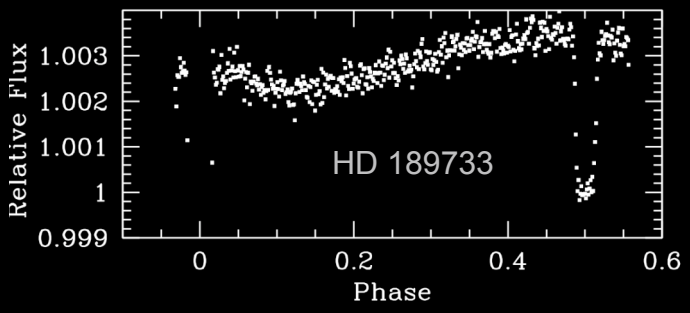
NASA/ESA/G. Bacon
Spitzer Space Telescope

Hot Jupiters





Harrington, Hansen et al., Science 2006



Knutson et al. 2007

Day/Night Temperature Gradients

Some hot Jupiters have thermal inversions and strong day/night temperature gradients. Current view: no robustly definitive correlation with host star properties.

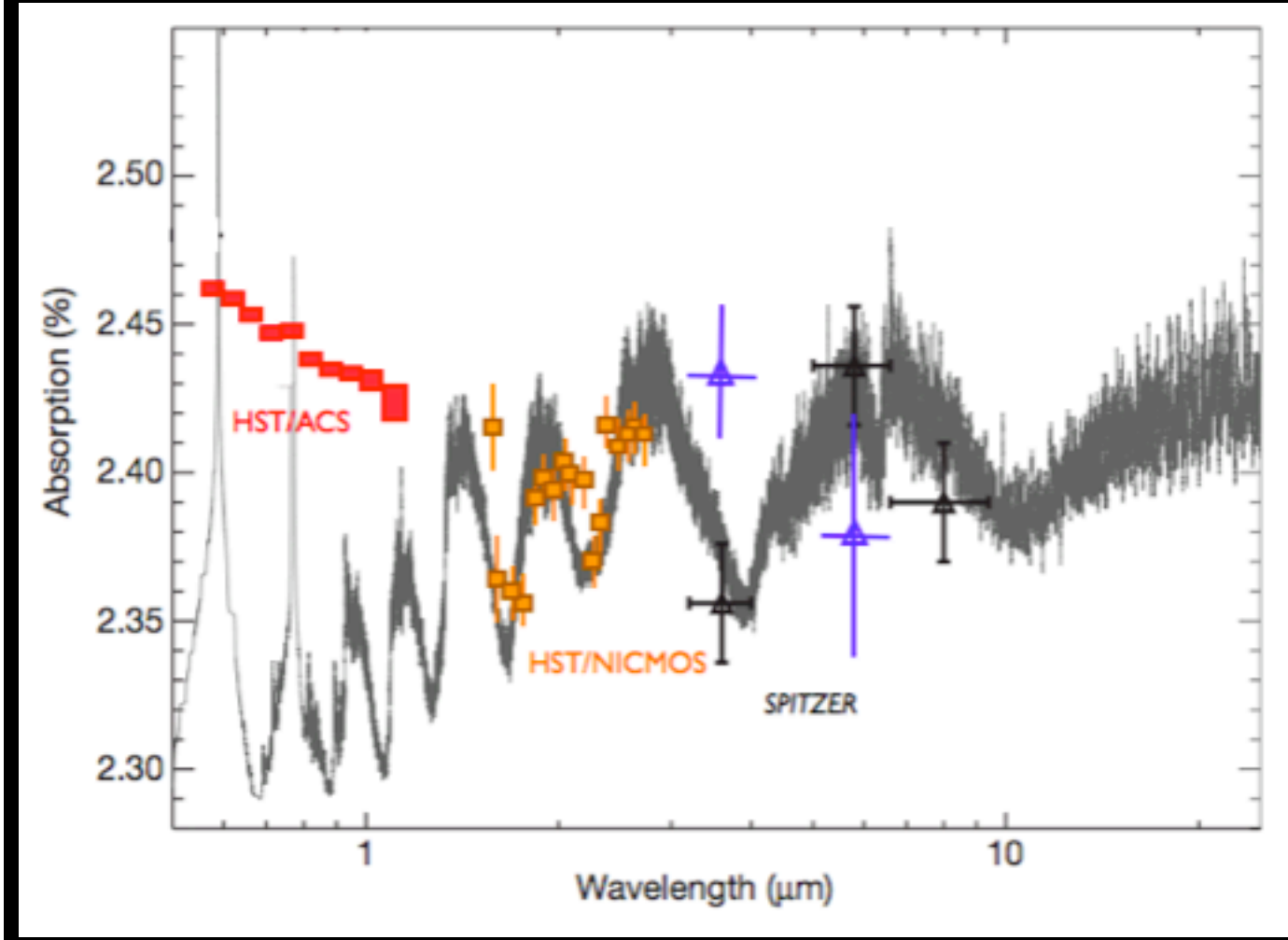
Seager 2008

Spitzer Exoplanets

Confirmation: Hot Jupiters are Hot
Atmospheric Water Vapor
Thermal Inversion
Day-Night Temperature (In)variation

Seager 2008

Identification of Atoms and Molecules and Solids



Courtesy F. Pont

HD 189733b
Na, H_2O, CH_4, CO_2, Hazes

HD 209458b
Na, H_2O
-detection of mild exospheric escape via H Ly α

Hot Jupiters to Hot Super Earths and Beyond

Spitzer's Legacy: Hot Jupiters

Hot Super Earths

Beyond

Seager 2008

Hot Super Earths #1

GJ 876d vs. 209458b

d= 5 pc	d = 47 pc
T ~ 800K	T~1200K
R ~ 0.1 R_J	R = 1.35R_J

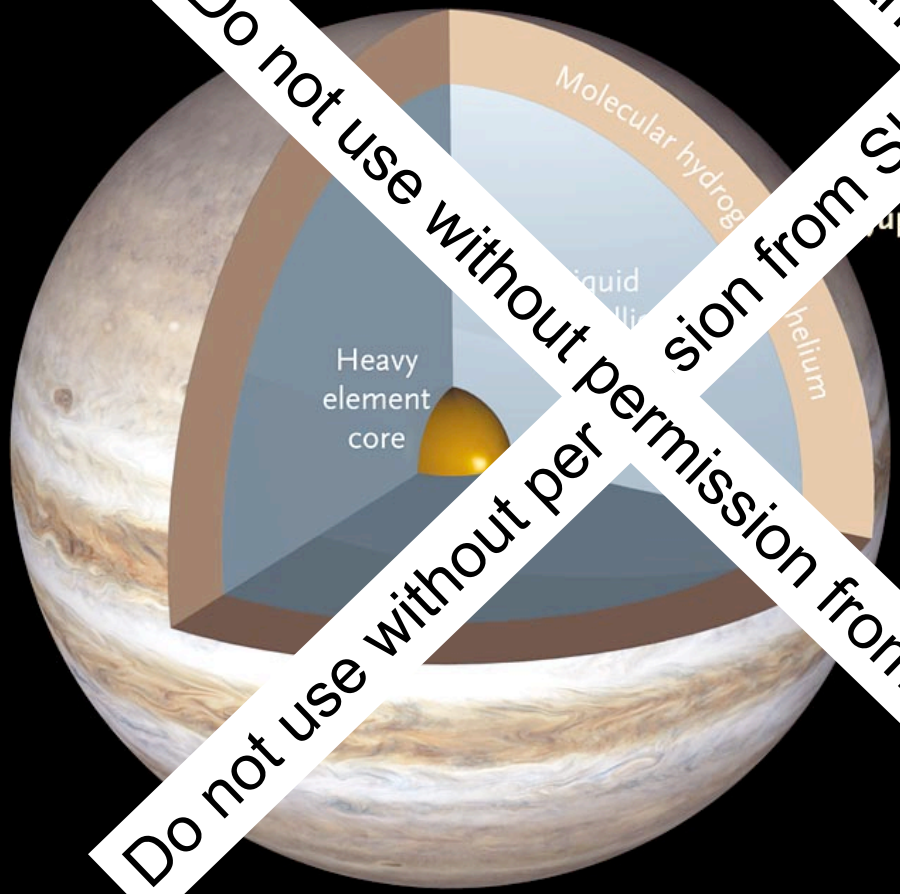
Fluxes will be comparable…

But no eclipse

GO-5 observations July 16/17 2008: 3/4 of an orbit
Goal was to investigate whether the planet is an atmosphereless rocky world via observations of thermal emission phase curve. Result: an upper limit only. Major limitation was unexpected IR variability of M star.

Seager and Deming, submitted

Hot Super Earth #2



Interiors

GJ 436b

Molecular hydrogen
and helium

Water

Iron and silicates

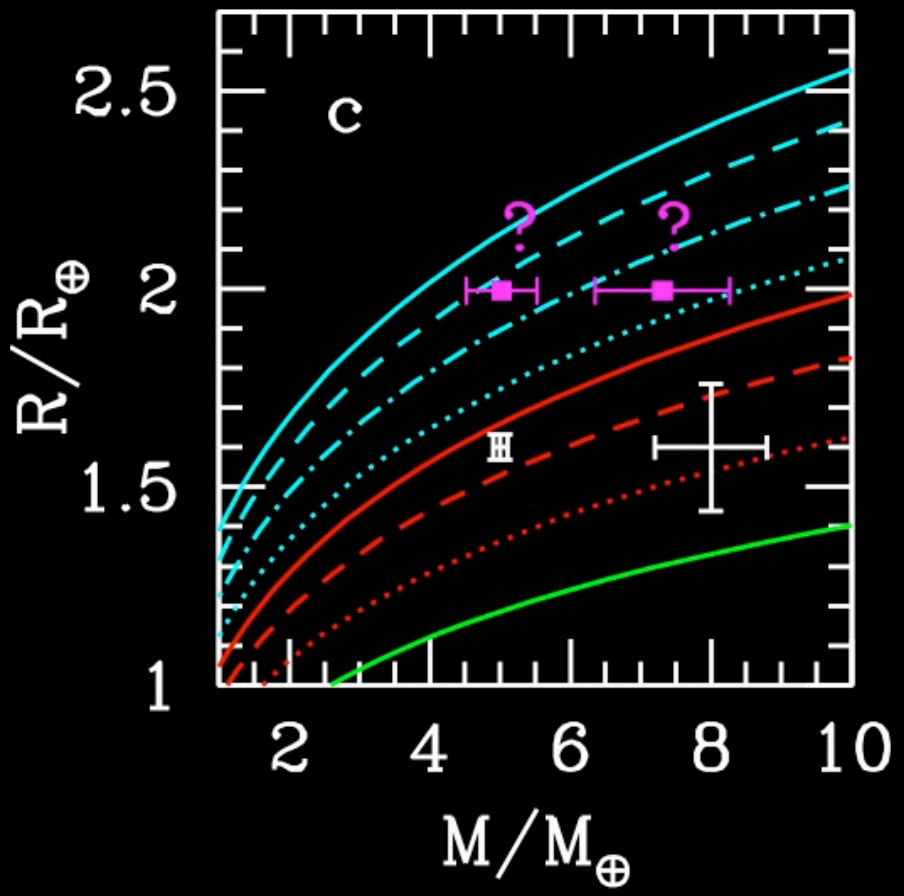
Earth-composition planet
with GJ 436b's mass

Silicates

Iron

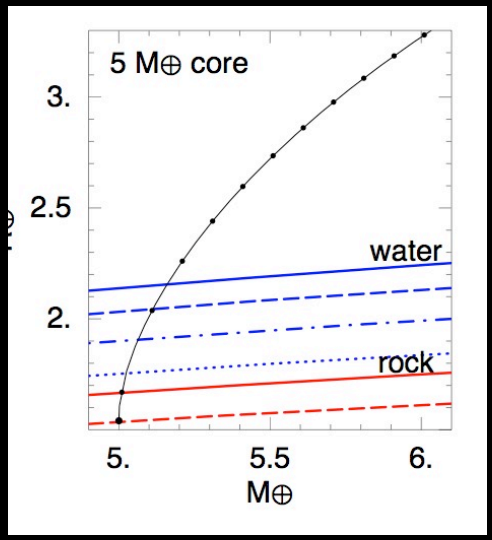
Casey Reid

Hot Super Earths #2



Seager, Kuchner, Hier-Majumder, Militzer 2007

Gillion et al. Warm Spitzer 100 Hours

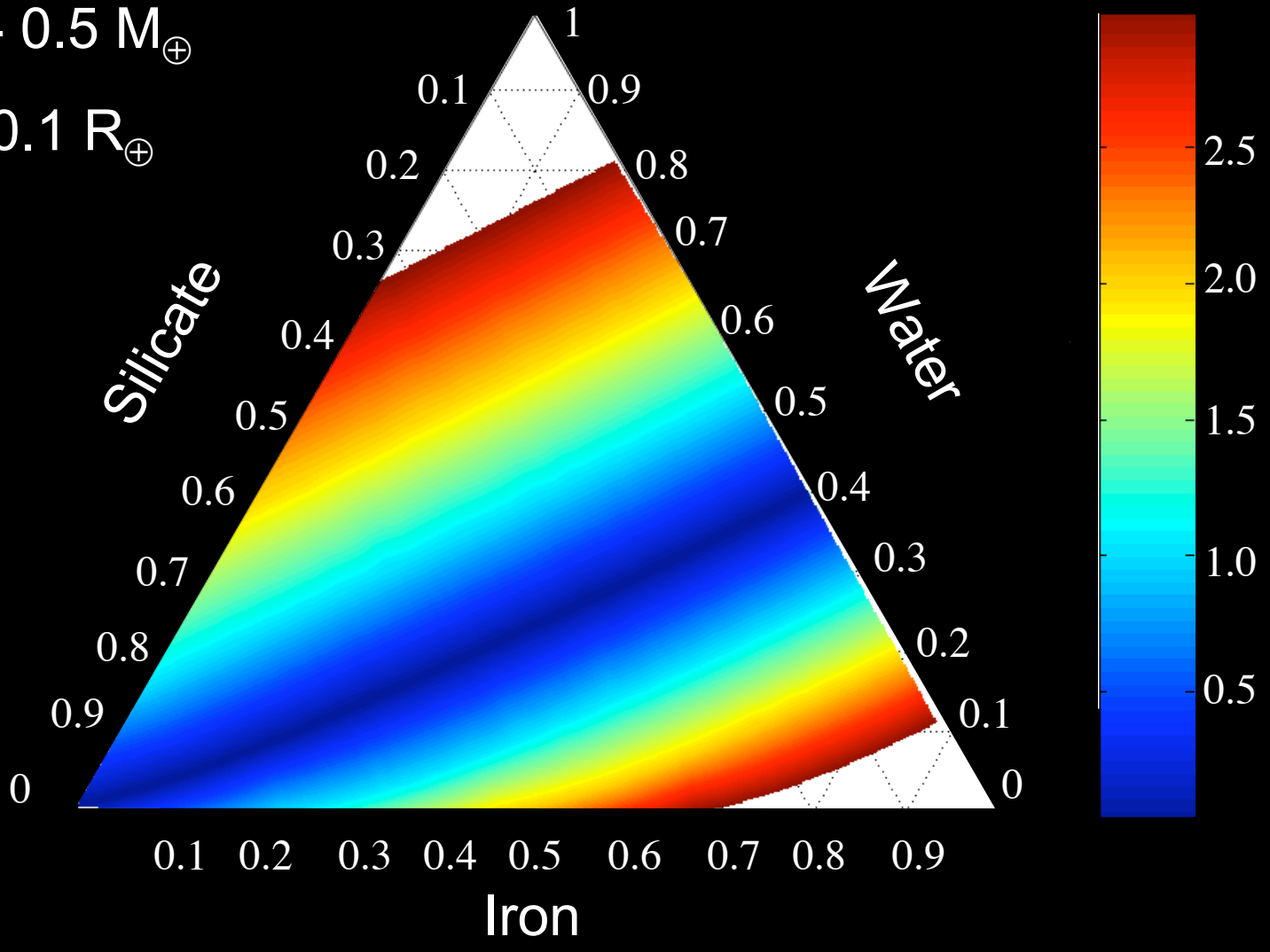


Adams, Seager, Elkins-Tanton 2008

Living with Uncertainty

10.0 +/- 0.5 $M_{\oplus}$

2.0 +/- 0.1 $R_{\oplus}$



Bright stars are required to reduced radius uncertainty

Zeng and Seager 2008

Hot Super Earths

The next wave of exoplanet discoveries will be about super Earths

M star variability could be a problem for planet atmosphere observations

Seager 2008

Hot Jupiters to Hot Super Earths and Beyond

Spitzer's Legacy: Hot Jupiters

Hot Super Earths

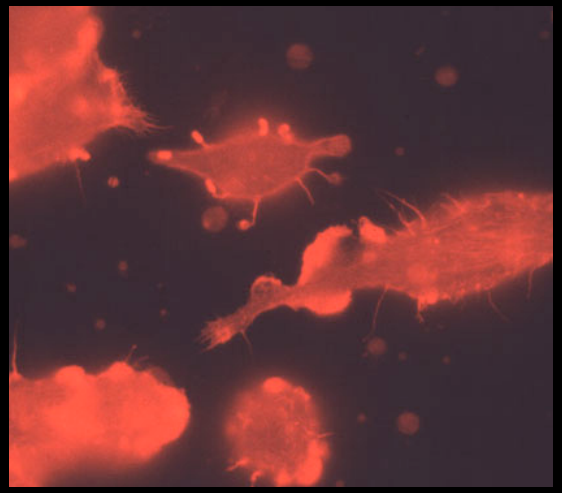
Beyond

Seager 2008


I WANT TO
BELIEVE

Alien Life

www.geocities.com/ artboook2001/alien-555.jpg

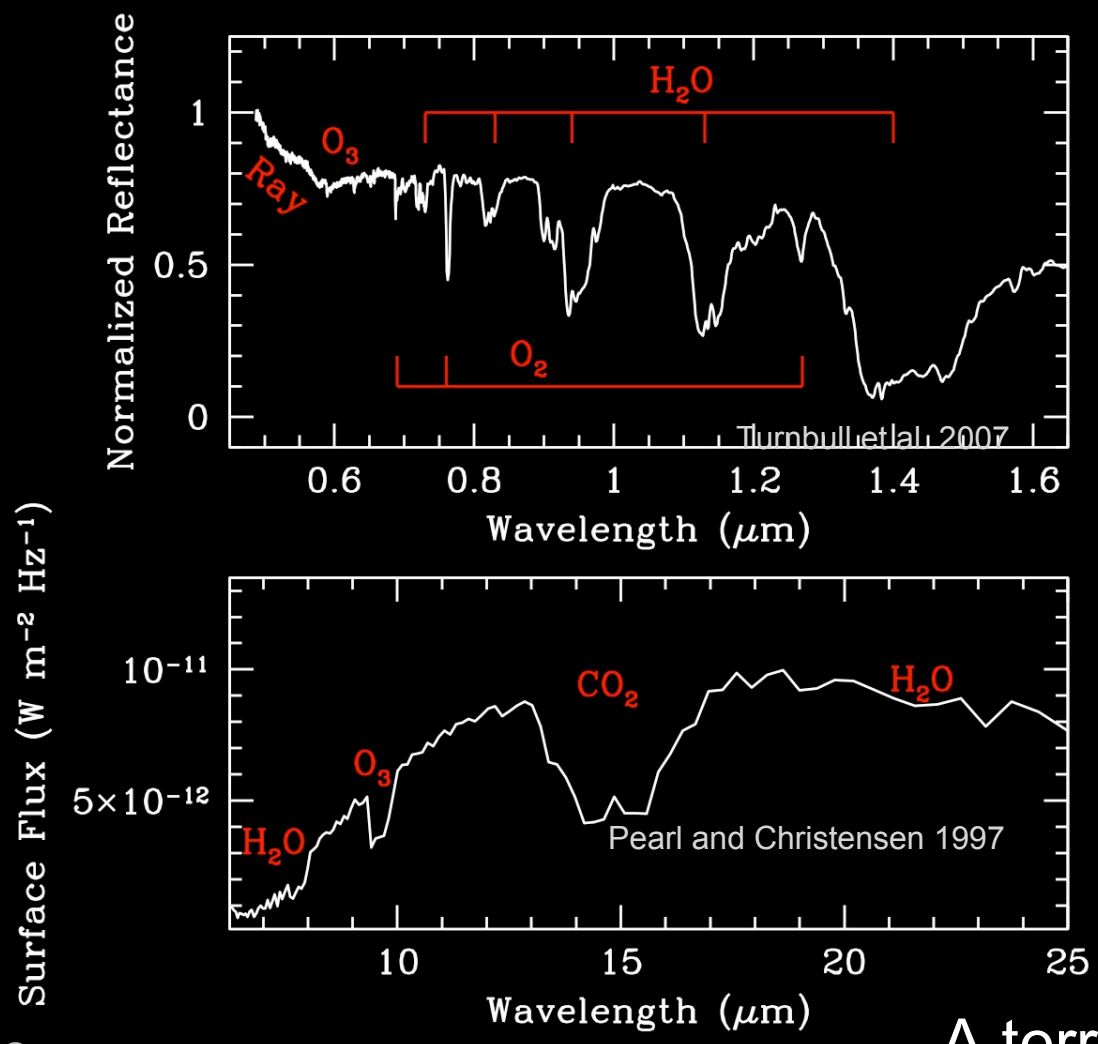


www.listeriablog.com/listeria2.jpg

"Nothing would be more tragic in the American exploration of space than to encounter alien life and fail to recognize it…" NRC report 2007

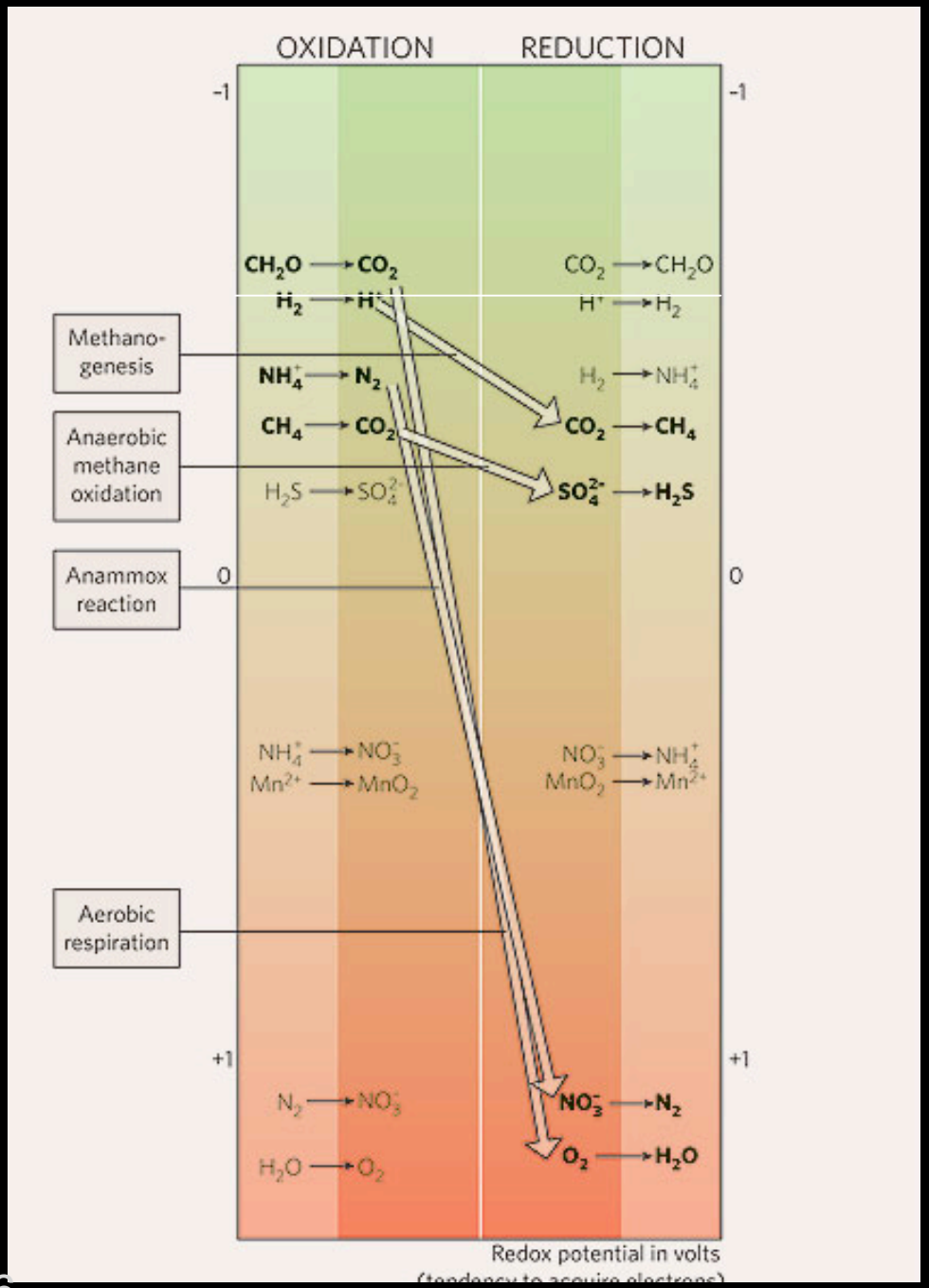
Seager 2008

Earth as an Exoplanet

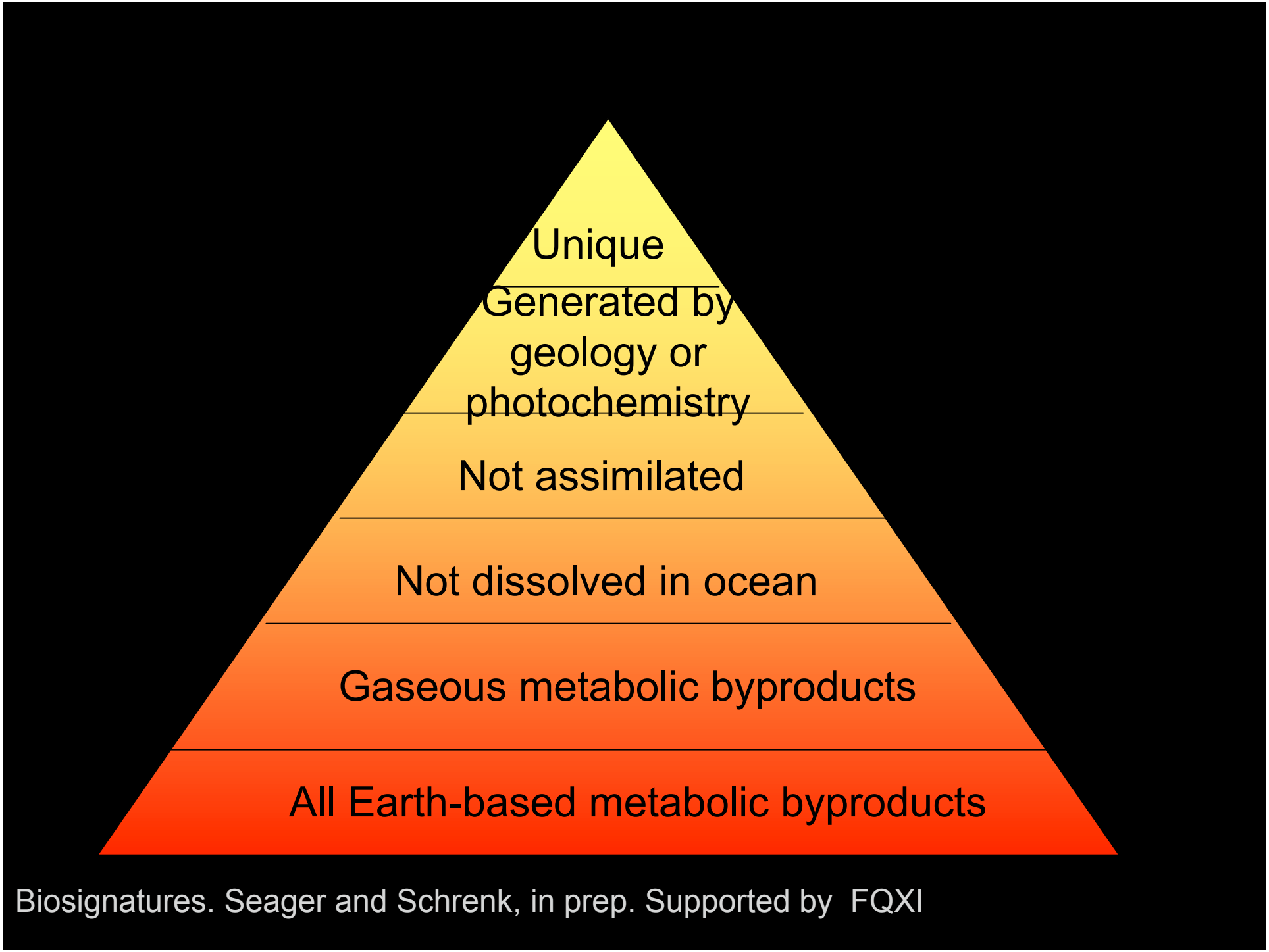


Seager 2008

A terracentric view!



Lane, Nature May 2006



Biosignatures. Seager and Schrenk, in prep. Supported by FQXI

Biosignatures

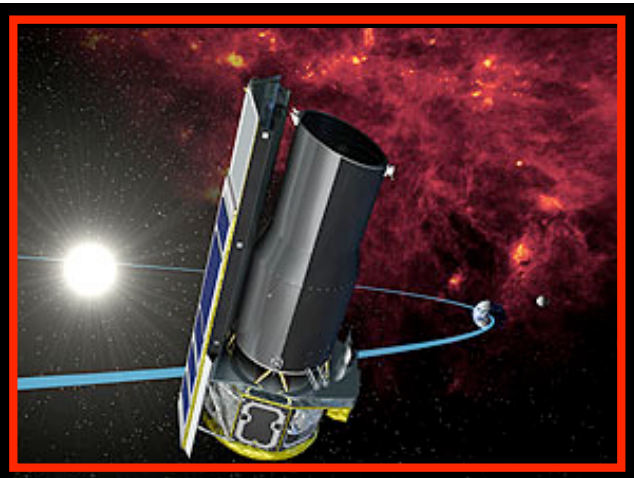
Life uses and exploits chemical energy gradients.

Metabolic byproduct gases may accumulate in the atmosphere.

JWST

We will study transiting super Earths orbiting small stars akin to *Spitzer/HST* observations of hot Jupiters transiting sun-like stars

Summary



- From Hot Jupiters …
  - Observation is now leading theory
  - A few robust observational highlights
- …. to Hot Super Earths
  - Report on GJ 876d
  - Prospects for super Earths around M stars may be clouded by stellar variability
  - Hope for Warm Spitzer super Earth transits
- And Beyond
  - Preparing to understand super Earths
  - We may have to live with uncertainty, but we can quantify it

Spitzer and HST have opened the field of comparative exoplanetology. The archived observations will be used for years and even decades to come.

Seager 2008